Orifice Plates for Furrow Flow Measurement: Part II - Design and Field Use

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ABSTRACT

ORIFICES, are potentially accurate furrow flow measurement devices. Flow measurement accuracy decreases with head loss. Orifice head loss will increase upstream infiltration. Thus, the head loss range must be constrained to maintain measurement accuracy. Design equations are developed for 3-hole orifice plates which give a 23:1 flow range with a 5:1 head loss range. A portable differential point gauge can measure submerged flow head loss to the nearest millimeter.

INTRODUCTION

Orifice plates are potentially accurate flow measurement devices due to their sensitivity to head. A companion paper (Trout, 1986) determined, through laboratory calibration, that (a) flow through small circular orifices was not affected by boundaries, caused by the furrow perimeter, the water surface, or adjacent orifices, within one half orifice diameter of the orifice edge; (b) square-edged furrow orifice submerged flow discharged coefficient is 0.625; (c) free flow coefficients vary with the orifice size and head and thus free flow use is not recommended; (d) the discharge coefficients are not affected by hole edge thickness up to a thickness/diameter ratio of 1/3; and (e) orifice discharge coefficients are sensitive to rounding of the upstream edge.

This paper will utilize these laboratory results to develop furrow orifice plate designs and determine measurement accuracies and limitations under field conditions.

The discharge equation for orifices is:

$$Q = C_d A \sqrt{2g(h+h_v)} = \frac{C_d A\sqrt{2gh}}{\sqrt{1-C_d^2(A/A_1)^2}} \qquad [1]$$

where Q = the flow rate (L^3/T)
C_d = the orifice discharge coefficient
A = orifice cross-sectional area (L^2)
g = acceleration of gravity (L/T^2)
h = piezometric head acting on the orifice (L)
h_v = velocity head acting on the orifice (L)
A_1 = the flow cross-sectional area immediately upstream of the orifice

As long as A_1/A is greater than 6, the effect of velocity head on discharge will be less than 0.5% and can be ignored. This ratio is usually exceeded in furrows.

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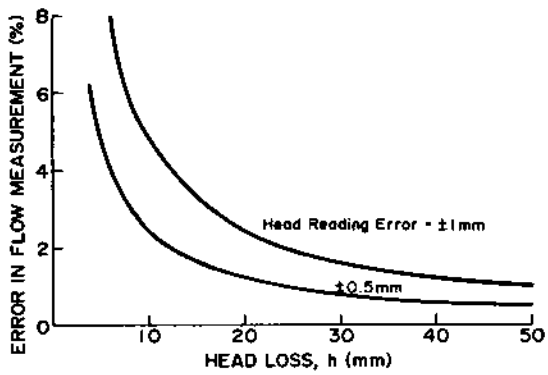

Fig. 1—Orifice flow measurement error as a function of head reading error and head loss (from equation [2] in Trout, 1986).

When head, h, and the diameter, D, of a circular orifice is measured in millimeters, the discharge, Q, is desired in liters per minute and the velocity head is negligible, equation [1] will be:

$$Q = 0.00660 C_d D^2 \sqrt{h} \qquad [2]$$

FURROW ORIFICE PLATE DESIGN AND CONSTRUCTION

The sensitivity of flow rate to head, which makes orifices accurate, severely limits their range. With a constant head reading precision, the relative error in a head reading, and thus flow measuremnt, will increase as the head decreases, as shown in Fig. 1. Head loss less than 10 mm should normally be avoided.

Furrow infiltration may increase with wetted perimeter. Consequently, when orifice plates are used to measure furrow outflows, the flow depth increase caused by the backwater in front of plates (or any flow measurement device) should be limited. Fig. 2 shows the predicted percent increase in upstream infiltration due to orifice head loss, h, in a 50 m long furrow on various slopes, S. The prediction assumes: (a) infiltration is linearly related to wetted perimeter (Fangmeier and Ramsey, 1978); (b) the furrow shape is described by a power curve with a top width, T, 8 times the normal depth, d_N, and a one-to-one side slope at the normal water surface or:

$$T = 8 d_N^{3/4} d^{1/4} \quad (d = \text{flow depth}) \qquad [3]$$

(c) the flow rate is 40 L/m, and (d) the Manning's roughness coefficient is 0.04. The relative infiltration increase is inversely proportional to the upstream measured furrow section length for sections longer than the effective backwater length (about 16 m at S=0.002 and 6 m at S=0.010 for h=50 mm). The effect also

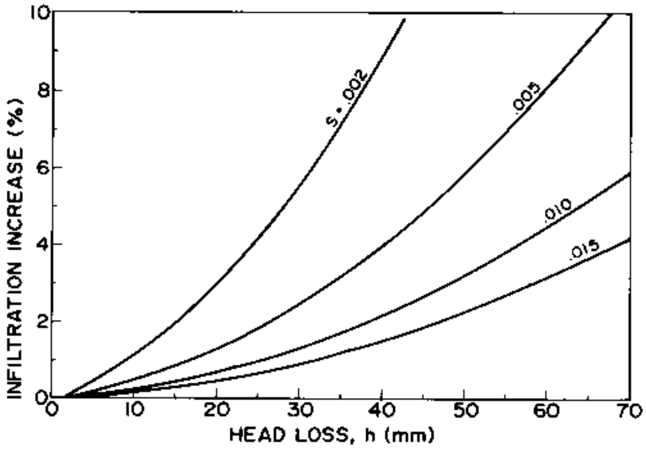

Fig. 2—Infiltration increase in a 50 m furrow section on various slopes, S, caused by measurement device head loss.

varies inversely with the flow rate and roughness coefficient product which affects the normal wetted perimeter. The figure shows that the orifice headloss generally should not exceed 50 mm and should be limited to 40 mm at the tail of short (<50 m) moderately sloped furrows sections, and that orifice plates should not be used in very flat furrows.

Consequently, the allowable head loss range for accurate furrow flow measurement is only about 10 mm to 50 mm or 5:1 which results in a range of flows of only 2.2:1. This range is not large enough for most conditions.

If two properly-sized orifices are used sequentially, the flow range with the 5:1 head ratio is increased to 5:1; if they are also used simultaneously, the range is 7:1. Using three holes sequentially yields a flow range of 11:1, using three holes in all combinations yields a range of 23:1. This range is adequate to cover most conditions. If the full range is not required, the head ratio should be reduced to allow some overlap of the ranges and more accurate measurement.

The calibration results show that orifices at these heads can be separated by as little as one-third the sum of their diameters without affecting the discharge coefficient (Trout, 1986). Consequently, several holes can be closely spaced on a plate and used concurrently to achieve the required range. Fig. 3 shows 3-hole orifice plate layout in which the small and medium, and medium and large holes are separated by at least half the sum of their diameters, making the effective separating boundary 1/2 diameter from the edges. Not using the small hole concurrently with the large hole on a 3-hole plate decreases the flow range only about 10% (from 23 to 21:1 with the 5:1 head range), but allows nesting the small hole between the other two and decreasing the total width. In this layout, the small hole is located far enough from the large one that its plug won't significantly affect the large hole's flow. Rubber stoppers are effective plugs for unused holes.

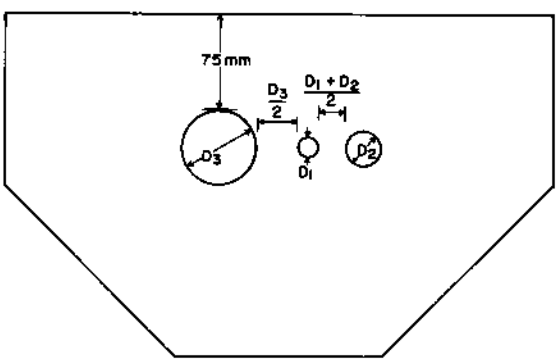

Fig. 3—Recommended furrow orifice plate design.

The holes should be sized such that all flows in the desired flow range are covered within the desired head range. The required sizes are determined by sizing the larger-sized orifice so that its capacity at the lowest head equals the capacity of all smaller orifices combined at the highest head. The small hole (diameter=D_1) must measure the lowest required flow, Q_L, at the lowest allowed head, h_L. Solving equation [2] for the diameter.:

$$D_1 = \left(\frac{Q_L}{0.0066 C_d \sqrt{h_L}} \right)^{1/2} \quad \text{[4]}$$

Since the flow capacity of the next larger orifice (diameter=D_2) at the lowest allowed head must equal the capacity of the small orifice at the highest permissible head, h_h; $D_1^2 \sqrt{h_h} = D_2^2 \sqrt{h_L}$ or:

$$D_2 = D_1 \left(\frac{h_h}{h_L} \right)^{1/4} \quad \text{[5]}$$

If a third orifice is required, its capacity at h_L must equal the capacity of the smaller holes combined at h_h:

$$D_3 = \left(D_1^2 + D_2^2 \right)^{1/2} \left(\frac{h_h}{h_L} \right)^{1/4} \quad \text{[6]}$$

This process could be continued for additional larger holes.

By inserting equations [4] through [6] in the equation for the maximum flow capacity with three orifices used together,

$$Q_h = 0.0066\, C_d (D_1^2 + D_2^2 + D_3^2) \sqrt{h_h} \quad \text{[7]}$$

the flow range, Q_h/Q_L, achievable with these orifices can be derived:

$$Q_h/Q_L = (h_h/h_L)^{1/2} + 2\,(h_h/h_L) + (h_h/h_L)^{3/2} \quad \text{[8]}$$

If the smallest hole is not used with the other two, the first term in equation [8] is dropped.

The orifice plate should be sized to fit the furrow with at least 50 mm (two inches) inserted into the furrow perimeter. Beveled lower edges make insertion easier. Plate material should permit easy cutting of a uniform square-edged hole, be durable enough that the edges don't wear quickly and maintain a smooth surface. The plates should be rigid enough to remain planar under the expected head and to insert easily into the soil. The plate thickness cannot be more than 1/3 the smallest hole diameter. Aluminum (3.2 mm [1/8 in.] thick) or 4.8 mm (3/16 in.) thick acrylic sheets are recommended.

The critical factor in constructing orifice plates is to achieve a hole with a sharp edge on the front face. Ree (1977) found discharge coefficient errors as large as 15% due to defects in the front edge of commercially made SCS type orifice plates (USDA-SCS, 1962). Experimenting with several bits, cutting speeds and lubricants may be required to achieve a satisfactory hole. Since acrylic has a low melting point, low cutting speeds may be required. Small holes were cut in acrylic with twist drill bits with a dulled cutting edge to prevent chipping. Holes larger than 20 mm diameter were cut with adjustable hole cutters with lathe tool bits specially reverse tapered so only the cutting tip touched the hole edge. The holes should be checked after drilling for chipping and rounding. If only one edge is satisfactory, it should be marked and used upstream.

Cutting the exact desired hole size is not critical. The nearest-sized bit available can be used. Consider available bits while making the design. Use caliper-measured hole size to determine discharge. If several plates are to be used interchangeably, their hole diameters must be within 0.5% of the mean to contain systematic errors due to hole size to $\pm 1\%$.

An advantage of orifice plates is cost. Commercially available furrow flumes cost \$70 to \$100. One hundred acrylic 3-holed plates were made to specifications in a commercial machine shop for about \$5.00 each including material. Also, their small size and shape make them very easy to transport to and in the field.

HEAD LOSS MEASUREMENT

Clear acrylic plastic was initially chosen for the orifice plates so that the head drop across the plate could be measured with a rule on the downstream side. This is similar to the method proposed by the SCS (USDA-SCS, 1962). However, due to trash and foam in the water, the menisci against the plate and rule, the sight parallax through the plate, and the uncomfortable position required to take readings, consistent accuracy of ± 2 mm could not be achieved.

A differential point gauge, shown in Figs. 4 and 5, was developed to achieve the required precision. The gauge is composed of two rods ground to a point on the lower end, which slide through a base plate which straddles the orifice plate. A rule is attached to the downstream rod and a pointer to the upstream, such that the pointer reads zero when the rod points are at the same elevation. Consequently, the pointer will directly indicate the elevation difference of the rod points, or by touching the points to the water surface, the water surface elevation difference in front of and behind the orifice plate. Under submerged flow conditions, this is the head loss, h.

The base plate should be grooved to fit snugly over the orifice plates. The rods must be moveable but still hold a position. Initially, rods with racks and pinion gears with handles were used to adjust the rods as most commercial point gauges are adjusted. These operate well if well made and if sediment and debris are kept out of the gears. A simpler arrangement is shown in the figures where two small leaf springs rub the rods and create enough friction to hold them at a setting but not enough to make them difficult to slide. A level bubble mounted on the base plate can be used to check that the gauge is horizontal across the plate. The base plate and rods can be made of PVC or acrylic, and the spring cut from band saw blades.

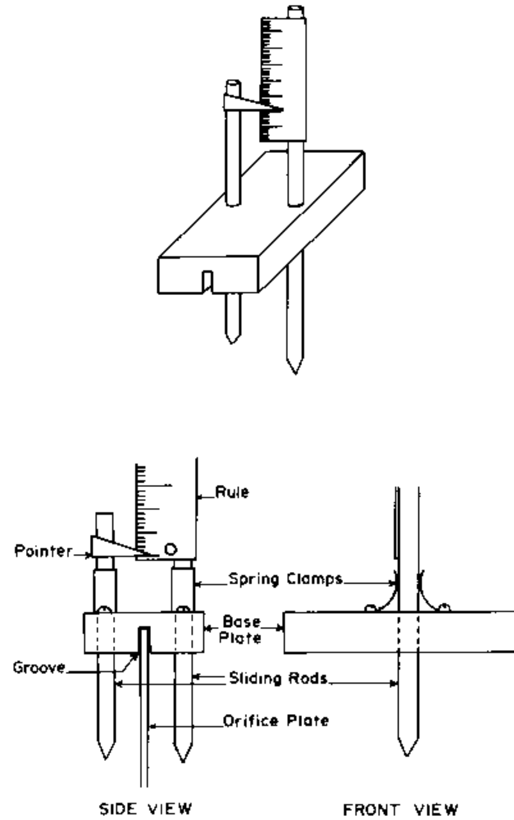

Fig. 4—Differential point gauge.

Fig. 5—Orifice plate installed in a furrow.

With this gauge, orifice head loss can be measured to the nearest millimeter (±0.5 mm) in still water and to ±1 mm in slightly turbulent water. Only one gauge is required per reader or site and is moved among plates.

INSTALLATION AND USE

Orifice plates are inserted vertically into the furrow perimeter roughly perpendicular to the flow. Robinson (1959) found that even when the orifice is 15 deg from perpendicular with the flow, the discharge relationship is not affected, so a visual check is sufficient. However, if the plate is not vertical, the differential point gauge will be tipped which will effectively alter the zero reading. The amount of the error due to this unlevel state will be proportional to the spacing between the rods. If the spacing is 30 mm, a 2 deg slope will change the zero by 1 mm. Consequently, if better than 5% accuracy is desired, either the orientation of the plate or the gauge base must be checked with a level when low heads (<20 mm) are measured. The plate top need not be horizontal across the furrow since the gauge points are spaced perpendicular to the plate. An 11 deg cross slope would be required to angle the point rods enough to create a 1% flow reading error.

Insert or drive the plate until the top of the hole is below the normal water surface. In steep channels, partial damming of the water downstream of the plate with a second plate or other stable obstruction may be necessary to raise the level to the top of the hole for submerged flow. The plate may be positioned laterally so that the hole or holes most likely to be used are near the center of the furrow. The unused holes can be plugged with rubber stoppers.

Soil can be excavated from in front of the plate to insure sufficient contraction (at least 1/2 diameter from the edges of the orifice), evenly distribute the flow, and to still the water surface for more accurate level measurement. Approach velocity will seldom be a concern. For example, the A_1/A ratio (equation [1]) will usually be larger than 6 even if the furrow is only three orifice diameters wide, the orifice bottom is only D/2 (the minimum recommended contraction) above the bed, and the upstream water surface is only 10 mm (the minimum recommended head) above the orifice top.

Judgement is required to select the orifice combination to measure an unknown flow rate. As flows change, hole combinations must be changed to maintain the head loss within the desired limits.

A primary concern with furrow orifice plates is partial plugging of the orifice with trash. Since the hole is submerged, partial plugging is sometimes difficult to detect. If the orifice is not clearly visible, check it for plugging before each reading by feeling the opening with your fingers.

The reduced flow velocity of the backwater will cause sediment to deposit upstream of the plate, although the flow acceleration at the orifice normally keeps it flushed from around the hole. Ensure that sediment has not built up close enough to the hole to affect the flow contraction. Sediment buildup near the plate which causes uneven velocity distribution or surface turbulence should also be cleaned out.

If orifice plugging is a problem, the plates should not be left unattended for long periods unless an overflow is provided. A notch in the top of the plate which is lower than the furrow banks but higher than the highest desired upstream water depth will provide a safety overflow.

If the hole is plugged or the flow disturbed in any way, a head loss reading should not be taken until the flow returns to near steady-state conditions. Because of the sensitive head-discharge relationship, orifices require more time to return to steady flow than flumes or weirs. The required time will vary with channel slope and orifice head loss, but will normally be between 1 and 5 min. Constant head loss readings will indicate steady-state conditions. This time lag problem makes orifice plates more difficult to use and less accurate under rapidly changing flow rate conditions.

The hole plugging and time lag problems are the two main disadvantages of using orifice plates in furrows and result in installed orifice plates normally taking two to five times as long to read as furrow flumes.

MEASUREMENT ACCURACY

Measurement errors in orifice plates can be caused by improper entrance conditions, unsteady flow, non-standard hole geometry, or errors in head measurement. Because of insensitivity to close boundaries, incomplete contraction will cause less than a 1% error as long as the boundaries are maintained at least 1/2 diameter from the holes. This problem seldom occurs in furrows because the accelerating flow keeps sediment flushed away from the edges of the hole. Any sediment buildup can be easily checked for and eliminated by excavation. Approach velocity caused errors will be less than 0.5% as long as the upstream channel area is at least six times the orifice area and the velocity is evenly distributed across the furrow. Uneven flow distribution will be caused by obstructions such as sediment dunes which direct the flow unevenly. Either problem can be solved by excavation. Because orifice plates return to steady state conditions slowly, measurements may inadvertently be taken during unsteady flow conditions. The error will decrease as steady conditions area approached and can be evaluated by head measurement over time. When the head change is less than the precision with which it can be measured, the error will be no larger than head measurement precision-caused error.

Circular holes can be cut and measured with calipers to within ±0.05 mm diameter. Since flow is proportional to the square of the diameter, this will cause less than a 1% flow reading uncertainty in any orifice larger than 10 mm diameter and less than 0.5% error in any orifice larger than 20 mm.

Rounding of the front edge of the orifice is a more serious and difficult to detect source of error. Even slight rounding or chipping will increase the discharge coefficient. Initial orifices constructed and tested had slight but visible rounding and chipping and discharge coefficients up to 4% higher than square-edged orifices. The edges of all orifices should be carefully checked for squareness after cutting and periodically over time.

Errors caused by head reading resolution or incorrect readings will vary with the head, as shown in Fig. 1. When the head is 10 mm, a reading resolution of ±0.5 mm will yield a flow resolution of only ±2.5, while at 25 mm head, the same reading precision will yield a flow within ±1%. Of course, in furrows with little slope, this improvement in measurement accuracy must be weighed against the higher and longer backwater caused by the head loss and its influence on furrow infiltration.

Accurate head readings require a differential or other point gauge arrangement on a still water surface. The zero reading must be within the desired head reading tolerances and gauge base within one degree of being horizontal across the orifice plate. The zero on the differential point gauge shown in Fig. 4 can be easily checked by placing it across a plate in standing water.

If all these potential errors are maintained within the tolerances given, the total error can be held to $\pm 4\%$ at low heads and $\pm 3\%$ for $h > 25$ mm.

The variability in furrow flow measurement device readings by several technicians measuring several flows in the field was measured (Trout and Mackey, 1985). The standard deviation of orifice plate differential point gauge readings was 1.2 mm, or about double the resolution and did not vary consistently with the reading. This implies a maximum reading error, defined as the 95% probability interval (ISO, 1978), of 2.4 mm, and would cause a maximum flow measurement error at 10 mm head of 11%, at 20 mm head of 6%, and at 40 mm head of 2.5%. Levels were not used to set the differential point gauges and more accurate leveling would reduce this error. The maximum flow rate error measured with furrow flumes with side gauges varied from 9% at low flows to 15% at high flows. The accuracy achieved with a 3.78 L (1 gal) container volumetric measurement varied from about 3% at low flows to 8% at 70 L/m.

Thus, although multi-holed orifice plates will normally be more accurate than flumes, the achievable accuracy probably will not be realized in the field, and accuracy will strongly depend upon the head loss created. A disadvantage of orifice plates relative to flumes is that the head loss is equivalent to the head and thus the backwater effects on infiltration (Fig. 2) will increase as the measurement accuracy increases. Long-throated flumes can operate with a head loss of only 10 to 20% of the upstream head and thus create less backwater storage. Volumetric measurement, of course, can only be used with free falling water such as gated pipe or siphon tube discharge.

CONCLUSIONS

1. Orifice plates are less expensive and more portable than other furrow flow measurement devices such as flumes.

2. Furrow orifices are more prone to plugging by trash and slower to return to steady flow conditions and thus require more time to take readings than flumes.

3. Carefully made orifices with differential point gauges to determine head can measure flows to within ± 3 to 4%, with accuracy increasing with the head. Field measurements, however, indicate that errors in the field may reach three times these values.

4. Orifice head creates backwater storage that will increase infiltration in the upstream furrow section. Head should therefore be limited to 50 mm in steep furrows (>1% slope) and 40 mm on moderately-sloped furrows (0.5% to 1%). On flat slopes, orifices generally should not be used.

5. The potential furrow flow measurement accuracy advantage of orifice plates will not be realized when furrow slopes are less than 0.005 or head loss is less than 20 mm.

References

1. Fangmeier, D. D., and M. K. Ramsey. 1978. Intake characteristics of irrigated furrows. TRANSACTIONS of the ASAE 21(4):696-700.

2. International Standard Organization (ISO). 1978. Measurement of fluid flow: Estimation of uncertainty of a flow rate measurement. International Standards ISO 5168, 1978 (E), available from ANSI, 1430 Broadway, New York, NY 10018.

3. Ree, W. O. 1977. How accurate are shop-made orifice plates. TRANSACTIONS of the ASAE 20(2):298-300.

4. Robinson, A. R. 1959. Orifice plates for furrow flow measurement. Unpublished report of the USDA-ARS Soil and Water Conservation Research Division and Colorado Agric. Exp. Station, Fort Collins, CO.

5. Trout, Thomas J., and Bruce E. Mackey. 1985. Inflow-outflow infiltration measurement accuracy. Unpublished report to be submitted to TRANSACTIONS of the ASAE.

6. Trout, Thomas J. 1986. Orifice plates for furrow flow measurement: Calibration. TRANSACTIONS of the ASAE 29(1):103-107, 111 (this issue).

7. USDA Soil Conservation Service. 1962. Measurement of irrigation water. SCS National Engineering Handbook, Section 15, Chapter 9, pp. 9-5 to 9-9.